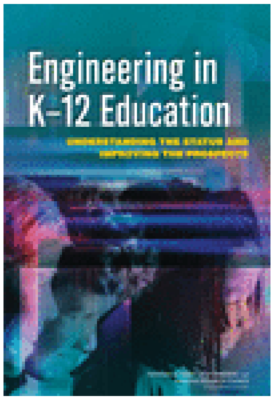

Engineering in K-12 Education: Understanding the Status and Improving the Prospects

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The Current State of K–12 Engineering Education

A major goal of this project was to determine the scope and nature of current efforts to teach engineering to K–12 students in the United States. How many programs are there, who developed them, and which students have they reached? What purposes do they serve? How do they present engineering and engineering design? How do they relate to science, mathematics, and technology? What pedagogical strategies do teachers use? Have outcomes data been collected, and how good are these data? We approached this task in two ways: (1) by reviewing curricula for teaching engineering concepts and skills in K–12 classrooms and (2) by reviewing relevant professional-development initiatives for teachers.

As it turns out, the curriculum landscape is extremely varied; in fact, no two curricula occupy the same "ecological" niche. This is not surprising, given the diverse origins of these materials and points of view of their creators. In addition, because there is no widespread agreement on what a K–12 engineering curriculum should include, the committee decided not to compare programs directly but to identify areas of relative emphasis and notable omissions. This approach revealed certain cross-cutting themes, which are discussed in detail later in this chapter.

Developing a curriculum does not guarantee that engineering education in K–12 will be successful. A critical factor is whether teachers—from elementary generalists to middle school and high school specialists—understand basic engineering concepts and are comfortable engaging in, and teaching, engi-

neering design. For this, teachers must either have appropriate background in mathematics, science, and technology, or they must collaborate with teachers who have this background. We held two data-gathering workshops to explore the professional-development situation for K–12 engineering educators. Information from those workshops is also included in this chapter.

Although the emphasis in this report is on engineering education in this country, the charge to the committee included a directive to find examples of pre-college engineering education in other nations, on the grounds that efforts elsewhere to introduce pre-college students to engineering might influence decisions here. The few initiatives we found are described briefly in an annex to this chapter.

Finally, we recognize that numerous efforts have been made to introduce engineering to K–12 students outside of formal school settings, through websites, contests, after-school programs, and summer programs. The committee charge did not require us to examine these informal K–12 activities. We note, however, that some of these initiatives appear to have increased students' awareness of and stimulated their interest in engineering (e.g., Melchior et al., 2005; TexPREP, 2003).

REVIEW OF CURRICULA

To identify K–12 engineering curricula, the committee relied on the joint efforts of committee members, Prof. Kenneth Welty,[1] University of Wisconsin-Stout, and project staff. The methods included reviews of websites of professional organizations, government agencies, and corporations with an interest in engineering education; searches of online curriculum clearinghouses and libraries; and direct communication with engineering educators, technology teachers, supervisors of state departments of education, and principal investigators of known K–12 engineering education programs and projects. In May 2008, the committee solicited public comments on a project summary, which brought several additional curricula to our attention.

Overall, the committee collected more than 10,000 pages of material, including lengthy narratives downloaded off the Web, material stored on compact disks, material assembled in three-ring binders, and material bound into textbooks. The materials ranged from 425 pages on a single

[1]The committee chose Prof. Welty because of his expertise in curriculum analysis, as well as his capacity as a co-principal investigator at the National Center for Engineering and Technology Education (NCETE) funded by the National Science Foundation. NCETE's research agenda complements the overall goals of this project.

topic—gliders—to just 46 pages on the huge topic of biotechnology. To ensure that patterns would be identified and meaningful conclusions drawn, the committee reviewed roughly equal numbers of curricula for each major K–12 grade band (i.e., elementary, middle, and high school).

Because of limitations on time and funding, as well as practical difficulties in locating some more obscure products, this curriculum review cannot be considered comprehensive. Nevertheless, the committee believes nearly all major initiatives and many less-prominent ones are included, thus providing a reasonable overview of the current state of K–12 engineering education in the United States. We are aware that there are individual courses not part of larger curricula that address engineering concepts and skills to varying degrees. These courses, typically developed and taught by technology educators, are not treated in our analysis, however.

Selection Criteria

To bound the analysis, the committee developed criteria to guide the selection of curricula that reflect the committee's consensus that design is the distinguishing characteristic of engineering. To be included in the study, therefore, curricula had to meet the following specifications:

- The curriculum must engage students in the engineering-design process or require that students analyze past solutions to engineering-design problems.
- The curriculum must explore certain concepts (e.g., systems, constraints, analysis, modeling, optimization) that are central to engineering thinking.
- The curriculum must include meaningful instances of mathematics, science, and technology.
- The curriculum must present engineering as relevant to individuals, society at large, or both.
- The curriculum must be of sufficient scale, maturity, and rigor to justify the time and resources required to conduct an analysis.[2]

[2]Specifically, each initiative had to be designed to be used by people and organizations outside the group responsible for its initial development. It also had to include at least one salient piece that had undergone field testing and subsequent revision and was no longer identified as a "draft." Finally, during the development of the initiative, it had to include some form of review of the initial concept, pilot or field testing, iterations based on feedback, an external evaluation, or a combination of these.

Review Process

The review process was overseen by Prof. Welty with the help of graduate fellows at NCETE. The committee initially underestimated the challenges of conducting in-depth reviews, such as the unique content, point of view, and organization of each curriculum and, often, their large size, which required many more hours of analysis than had been originally budgeted. As a result, the plan for reviews had to be modified midway through the project. Ultimately, we conducted two types of reviews: in-depth content analyses and descriptive summaries.

In-depth reviews were conducted on curricula that (1) appeared to be widely used in schools, (2) appeared to have longevity, or (3) had other special characteristics that merited close examination. The in-depth reviews covered all three grade bands (Table 4-1).

TABLE 4-1 Curricula Included in the Study[a]

Title	Developer
Pre-K	
1. Young Scientist Series—Building Structures	Educational Development Center
Elementary School	
2. The Academy of Engineering (also for middle school and high school)	PCS Edventures!
3. Children Designing and Engineering	The College of New Jersey
4. City Technology/Stuff That Works	City College of New York
5. Engineering is Elementary	Boston Museum of Science
6. Full Option Science System	Lawrence Hall of Science
7. Insights (Structures Unit)	Education Development Center
8. Invention, Innovation, and Inquiry	International Technology Education Association
9. A World in Motion	Society for Automotive Engineers
Middle School	
10. Building Math	Boston Museum of Science
11. Design and Discovery	Intel Corporation
12. Gateway to Technology	Project Lead the Way
13. The Infinity Project (Middle School)	Southern Methodist University
14. Learning by Design	Georgia Institute of Technology
15 LEGO® Engineering	Tufts University
16. TECH-Know	Technology Student Association

continued

TABLE 4-1 Continued

Title	Developer
17. Technology Education: Learning by Design	Hofstra University
18. A World in Motion	Society for Automotive Engineers
High School	
19. Designing for Tomorrow	Ford Partnership for Advanced Studies
20. DTEACh	University of Texas at Austin
21. Engineering: An Introduction for High School	Arizona State University/CK12 Foundation
22. Engineering by Design	International Technology Education Association
23. Engineering the Future	Boston Museum of Science
24. Engineering Your Future	Gomez, Oakes, Leone/Great Lakes Press
25. Engineers of the Future	(Curriculum based on design and technology courses developed in the United Kingdom)
26. Exploring Design and Engineering	The College of New Jersey
27. The Infinity Project	Southern Methodist University
28. INSPIRES	University of Maryland Baltimore County
29. Introduction to Engineering Design	Project Lead the Way
30. Material World Modules	Northwestern University
31. Principles of Engineering	New York State Dept. of Education/Hofstra
32. What is Engineering?	Johns Hopkins University
33. A World in Motion	Society of Automotive Engineers
Other	
34. TeachEngineering.org	Five-university collaboration (part of the National Science Digital Library)

[a]Curricula shaded in gray received in-depth reviews.

Each in-depth review included a detailed inventory of the content of the curriculum that addressed concepts and skills related to engineering, technology, mathematics, and science. The research team also identified stated goals, pedagogical strategies, prominent activities, and treatment (if any) of content standards. If available, the team also documented how extensively the curriculum had been implemented and findings related to its impact. The authors of the curriculum were contacted, as needed, to provide background information, clarify details, or confirm researchers' findings. Detailed written reports for each in-depth review were read and discussed by the committee. Descriptive summaries were prepared for the other curricular documents.

The descriptive summaries can be found in Appendix B and the in-depth reviews in Appendix C, included on the CD in the back cover of the report.

CONCEPTUAL MODEL OF ENGINEERING CURRICULA

The search for K–12 engineering education curricula turned up a wide variety of products from many different sources. Each curriculum had its own personality, and no two were completely alike in mission, content, format, or pedagogy. To deal with this complexity, Prof. Welty developed a "beads-and-threads" model (Figure 4-1) that enabled us to analyze the curricula in a systematic way using a manageable set of key variables.

The beads represent the "packaging" in which the engineering content of the curriculum is delivered to students. Most of the curricular materials used interesting technologies to package content into manageable chunks. For example, "The Infinity Project" focused on technologies likely to be of interest to students, such as the Internet and cell phones, digital video and movie special effects, and electronic music. Other developers organized materials around hands-on learning activities familiar to and popular with many students and teachers. For example, the middle school program of "Project Lead the Way," *Gateway to Technology*, includes activities for making and testing CO_2-powered dragsters, magnetic-levitation vehicles, water-bottle rockets, model rockets, and Rube Goldberg devices.

The content of several curricula was organized around the design process. For example, the "Design and Discovery" curriculum, by Intel Corporation, features lessons and learning activities for identifying problems, gathering information, brainstorming solutions, drawing plans, making models, building prototypes, and making presentations. Prominent local or regional industries, such as Ocean Spray Cranberries, Inc., were used as examples in interdisciplinary thematic units in the "Children Designing and Engineering" materials, developed at The College of New Jersey. The material in one curriculum, "Engineering is Elementary," was organized around traditional fields of engineering (e.g., civil, environmental, electrical, agricultural, and mechanical engineering).

In the conceptual model, the threads, which run through the beads, represent the core concepts and basic skills a curriculum is designed to impart, independent of the particular packaging. Three threads, mathematics, science, and technology, represent domain knowledge in these subjects that is used in engineering design. A fourth thread represents the engineering design process. The design thread incorporates a number of spe-

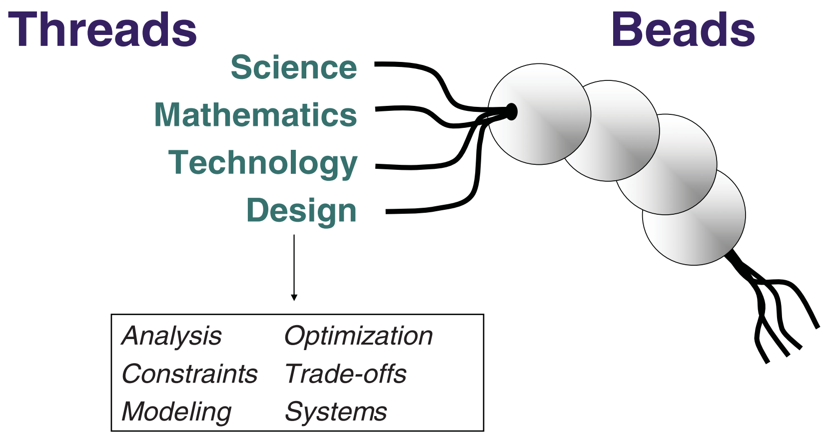

FIGURE 4-1 A beads-and-threads model of K–12 engineering curricula.

cific attributes of engineering design, such as analysis, constraints, modeling, optimization, and systems. The sections below describe of how these threads play out in the curricula.

The Mathematics Thread

We defined mathematics as patterns and relationships among quantities, numbers, and shapes. Specific branches of mathematics include arithmetic, geometry, algebra, trigonometry, and calculus. Our analysis suggests that mathematics is a thin thread running through the beads in most of the K–12 engineering curricula.[3] The thinness of the thread reflects the limited role of mathematics in the objectives, learning activities, and assessment tools of the curricula.

The mathematics used in the curricular materials reviewed by the committee involved mostly gathering, organizing, analyzing, interpreting, and presenting data. For example, in the "A World in Motion" curriculum, students build and test small vehicles (e.g., gliders, motorized cars, balloon-

[3] A separate analysis of curriculum, assessment, and professional development materials for three Project Lead the Way courses found explicit integration of mathematics "was apparent, but weakly so" (Prevost et al., 2009).

powered cars, wind-propelled skimmers). The testing involves measuring speed, distance, direction, and duration in conjunction with the systematic manipulation of key variables that affect vehicle performance (e.g., balloon inflation, sail size and shape, gear ratios, wing placement, nose weight). The data are organized into tables or graphs to see if they reveal patterns and relationships among the variables. The conclusions based on the data are then used to inform the design of subsequent vehicles.

Similar instances of gathering and using data for vehicle design were found in the *Models and Designs* unit in the "Full Option Science System" and the *Gateway to Technology* unit of "Project Lead the Way." Other materials engage students in counting and measuring, completing tables, drawing graphs, and making inferences, such as evaluating pump dispensers, conducting surveys, and testing materials.

Engineers often use mathematical equations and formulas to solve for unknowns. Young people can learn about the utility of this application of math in various ways, such as by calculating the amount of current in a circuit based on known values for voltage and resistance or determining the output force of a mechanism based on a given input force and a known gear ratio. Several instances of this kind were found in the "Engineering the Future" curriculum. In one activity, students calculate the weight of a proposed product (an organizer) based on three different materials prior to prototyping. Another requires that students calculate the mechanical advantage of a lever to determine how much force is required to test the strength of concrete.

However, most of the mathematics in the "Engineering the Future" curriculum is used to teach science concepts by illustrating relationships between variables, rather than to assist in solving design problems. For example, simple algebraic equations are used to represent the relationship between the cross-section of a pipe and its resistance to fluid flow, to calculate the output pressure of a hydraulic pump, and to determine the power produced by an electrical circuit. In these cases, mathematics is used to build domain knowledge in much the same way mathematics is used in science classes.

Several projects (e.g., "A World in Motion," "Building Math," *Gateway to Technology*, "Design and Discovery," "Designing for Tomorrow") introduce and require the application of basic geometry principles in conjunction with the development of technical drawings. For example, "Engineering the Future" includes lessons dealing with the concepts of scale and X, Y, and Z axes in the context of making orthographic, isometric, oblique, and perspective drawings. *Introduction to Engineering Design*, a unit in "Project

Lead the Way," addresses basic geometry in some detail in conjunction with the exploration of the modeling of solids using computer-aided design software. In this curriculum, students identify geometric shapes (e.g., ellipses, triangles, polygons), calculate surface area and volume, use Cartesian coordinates, and use addition and subtraction to create geometric shapes.

One strategy for increasing the mathematics content in some curricula was to include mathematical concepts in supplementary materials as enrichment activities. This approach might be characterized as a thread along the outside of the beads. The peripheral placement of the thread indicates that enrichment activities are optional, rather than integral to the unit but complement or extend instruction.

This approach was found in materials associated with projects in "Children Designing and Engineering," "Models and Designs," "Material World Modules," and "A World in Motion." For example, in an "extension activity" in "Models and Designs," students are asked to determine how long it took them to make an electrical device called a "hum dinger" (e.g., fastest time, slowest time, average time, total time). In an optional mathematics assignment in the *Gliders* unit of "A World in Motion," students determine the mathematical properties of different wing shapes (e.g., area, mean chord length, aspect ratio). At the high school level, the "Materials World Modules" invites teachers to engage students in using the formula for Young's modulus to determine the deflection of a fishing pole made out of drinking straws.

Mathematics is a dominant thread in "The Infinity Project" and "Building Math." The latter is designed to teach students how principles learned in middle school algebra can be used in the context of engineering challenges. For example, in the *Amazon Mission* unit, students design an insulated carrier for transporting malaria medicine, a filtration system for removing mercury from water, and an intervention plan for containing the spread of a flu virus. Like most of the other curricula reviewed, "Building Math" also requires that students collect data, make graphs, and interpret patterns, related to, for example, the insulating properties of materials; the flow of water through holes of different sizes; the deflection of materials based on their length, thickness, and shape; and the effect of angles on the speed of an object sliding down a string. A major goal of the "Building Math" curriculum is to teach students that engineers use mathematics to minimize guesswork in designing solutions to problems.

"The Infinity Project" is one of the few initiatives in which advanced algebra and trigonometry are introduced in engineering contexts. This curriculum encourages students to uncover, examine, and apply basic

mathematical principles that underlie common digital communication and information technologies. Binary numbers, matrix operations, polynomials, and other forms of mathematics are presented as essential content for synthesizing music, compressing video, and encrypting data, and mathematical concepts and equations are presented as tools used by engineers to create or improve a given digital technology or system. In addition, the laboratory activities require that students use mathematics and mathematical reasoning to design, simulate, and explore digital communication and information technologies.

Engineers often develop mathematical models featuring the key variables in a process, system, or device. The variables include forces that act on a structure, the length of time required for a process, or the distance an object moves. The relationships between variables are represented by equations that can be used to test ideas, predict performance, and inform design decisions. However, our review of curricula did not find any projects or units in which students were instructed to develop and use mathematical models to assist them in designing solutions to problems.

The Science Thread

We defined "science" as the study of the natural world, including the laws of nature associated with physics, chemistry, and biology and the treatment or application of facts, principles, concepts, or conventions associated with these disciplines. Our analysis suggests that science is a moderately thick thread composed of two strands, (1) science concepts related to engineering topics and problems and (2) scientific modes of inquiry that build knowledge and inform design decisions.

The First Strand

The most common science topics in the first strand found in K–12 engineering curricula relate to materials, mechanisms, electricity, energy, and structures and typically involve concepts such as force, work, motion, torque, friction, voltage, current, and resistance. In the curricula, most of these concepts are presented in the form of encyclopedia-like explanations that are subsequently reinforced in laboratory activities.

"Engineering is Elementary" includes concepts related to water, sound, plants, and organisms. At the high school level, "Material World Modules" address natural degradation processes, bioluminescence and chemilumi-

nescence, thermal and electrical conductivity, compressive and tensile forces on atoms, the relationship between molecular weight and viscosity, and the absorption and release of energy by molecular bonds.

The Second Strand

The second strand, scientific inquiry, is a major theme in several curricula, mostly to explore the interface between science and technology. For example, in the unit on *Composites* in "Material World Modules," students make and test foam beams laminated with varying amounts of paper to determine the strength and stiffness of composite materials. Similar experiments related to materials, structures, electrical circuits, and mechanisms are included in "A World in Motion," *Building Structures with Young Children*, a unit in the "Young Scientist Series," "Children Designing and Engineering," "City Technology," "Design and Discovery," "Engineering is Elementary," and "Engineering the Future." The results of these investigations are often applied in subsequent design activities.

Another way scientific inquiry is used in the curricula is related to the collection of data to inform engineering design decisions. For example, the second challenge in "A World in Motion" requires that students conduct investigations to determine the effect of different gear ratios on the speed and torque of a motorized toy vehicle. In some cases, scientific inquiry is used to discover, illuminate, or validate a law of nature, as might be done in a science classroom. For example, in *Gateway to Technology*, students experience Newton's Third Law by sitting on a scooter pointed in one direction, throwing a medicine ball in the opposite direction, and noting the direction and velocity of the scooter in relation to the direction and force used to throw the ball.

Many curricula engage students in scientific inquiry and inquiry-based learning in a symbiotic way. Several curricula introduce students to the basic principles of scientific investigation under the auspices of doing science. For example, "City Technology," "Material World Modules," and "A World in Motion" all stress the importance of manipulating one variable at a time while keeping the other variables constant. Learning activities in these programs include investigations that apply this principle in the contexts of packaging, structures, materials, and flight. In addition to teaching students about scientific investigations, they engage students in the generation, testing, revision, and validation of their ideas about protecting goods, making things stronger, and making models fly. In this sense, these curricula use scientific inquiry as a pedagogical strategy for building student knowledge of engineering design.

The Technology Thread

We defined "technology" as the study of the human-made world, specifically the knowledge, techniques, systems, and artifacts created by humans to satisfy their wants and needs. Our analysis suggests that technology in K–12 engineering curricula is a thick thread that often runs alongside the beads, rather than through them.

In most cases, the study of technology in K–12 curricula is used to build domain knowledge and develop a vocabulary for describing, discussing, and explaining a given technology. The emphasis on technical content is apparent in materials developed for "Project Lead the Way" and "The Infinity Project," both of which feature detailed treatments of specific technologies, such as digital electronics, digital communication and information technologies, automation, computer-aided design, and computer-aided manufacturing.

In some curricula, technologies are presented as concrete examples of scientific principles, especially in curricular materials that use engineering ideas or contexts to enrich science and mathematics learning. For example, a unit on composite materials in "Material World Modules" features discussions on technologies ranging from ancient bricks and clay pots to modern tennis rackets and automobile tires.

Some curricular materials are designed, at least in part, to improve technological literacy. For example, the central focus of the books written for "City Technology" is to "engage elementary children with the core ideas and processes of technology (or engineering, if you prefer)." The goal of "Engineering is Elementary" is to "tap into children's natural curiosity to promote [the] learning of engineering and technology concepts." "Exploring Design and Engineering" "help[s] youngsters discover the 'human-made world,' its design and development." "Engineering the Future" is intended to "help . . . high school students understand the ways in which they will engineer the world of the future—whether or not they pursue technical careers." "Invention, Innovation, and Inquiry" was created to "provide professional support for teachers interested in technological literacy in education."

The Design Thread

We defined "engineering design" as a purposeful, iterative process with an explicit goal governed by specifications and constraints. Our analysis suggests that design in K–12 engineering curricula is a strong, thick thread.

Virtually all of the curricula present a paradigm for designing solutions to problems that include a cyclical pattern of steps. Although the words and

phrases used to describe the design process vary from one curriculum to another, the basic approaches are analogous. For example, on the elementary level in "A World in Motion," the design process is organized around themes, such as setting goals, building knowledge, designing, building, testing, and presenting. Similarly, in a project in the "Children Designing and Engineering"curriculum, student design teams are instructed to "know the problem, explore ideas, plan and develop, test, and present."

The patterns are similar in curricula on the middle school and high school levels. For example, in "The Infinity Project," the design process includes the following steps:

- Identify the problem or objective.
- Define goals and identify the constraints.
- Research and gather information.
- Create potential design solutions.
- Analyze the viability of solutions.
- Choose the most appropriate solution.
- Build and implement the design.
- Test and evaluate the design.
- Repeat all steps as necessary.

Analysis

We defined "analysis" as a systematic, detailed examination intended to (1) define or clarify problems, (2) inform design decisions, (3) predict or assess performance, (4) determine economic feasibility, (5) evaluate alternatives, or (6) investigate failures. Our analysis revealed isolated instances of the first three applications of analysis and even fewer instances of the next three. Overall, analysis was rarely an explicit, recurring theme in a design process. Thus in our model, analysis is characterized as a fragment of thread attached to the design thread.

In most of the curricula, the first step in a design activity is to pose a problem or define a task. For example, the first three challenges in "A World in Motion" are framed in the context of designing toy vehicles for a fictitious company. In all three, the challenge to elementary and middle school students is to analyze the contents of a letter or request for proposals to identify the problem and specifications of a successful solution. Similar problem scenarios appear in the *Building Structure with Young Children* unit in the "Young Scientists Series," "Building Math," "Children Designing and Engi-

neering," "Engineering is Elementary," *Gateway to Technology*, and "Introduction to Engineering Design." All of these scenarios require basic reading comprehension but very little in the way of engineering analysis.

"City Technology" is one of the few curricula that engages students in a robust analysis to identify and define a problem. In one unit, *Designed Environments: Places, Practices, Plans*, elementary students monitor classroom procedures, identify problems, design and implement new procedures, evaluate the new procedures based on data, and use the findings of the evaluation to redesign the procedures as needed. A similar analysis is conducted to identify problems and develop design criteria to improve the configuration of the classroom.

Some of the materials engage students in a detailed analysis of everyday products using a process of reverse engineering. This is the predominant approach in materials in the "Design and Discovery," "City Technology," and "Designing for Tomorrow" curricula. For example, in a lesson in "Designing for Tomorrow," high school students analyze hand-powered can openers in terms of their primary and secondary functions, usability in different contexts, aesthetic qualities, and salient features. In the "Design and Discovery" curriculum, students dissect digital and mechanical alarm clocks to identify basic components and determine the relationships between form and function. The goals of these analyses are to understand how things work, to appreciate attention to detail, and to identify the strengths and shortcomings of given designs.

Engaging students in redesigning an existing product, rather than developing an original design, is also a major strategy in "City Technology," "Design and Discovery," and "Designing for Tomorrow." Students first analyze the performance of simple devices from a user's point of view. For example, in one "City Technology" unit, elementary students examine paper and plastic bags. In the "Design and Discovery" curriculum, middle school students study backpacks, toothpaste caps, and water bottles. In the "Designing for Tomorrow" curriculum, high school students investigate kitchen tools and training cups for toddlers. The analyses are then used to identify problems and/or opportunities for improving the design of the objects.

Most of the curricula include steps for assessing the performance of the final design, a type of analysis that includes both qualitative and quantitative techniques to determine how well the final design solves the original design problem. Examples of this kind of analysis can be found in "A World in Motion," "City Technology," "Design and Discovery," "Engineering is Elementary," and "Material World Modules."

Prior to implementing a design, engineers make decisions based on evidence that a given design will work; they rarely rely on trial and error. The evidence is often based on an analysis that predicts performance for a given configuration of variables. In several curricular projects, students are required to manipulate and test variables in various configurations to discover the patterns that can inform or optimize a design. This form of analysis is found in "A World in Motion," "City Technology," "Engineering is Elementary," and "Material World Modules." One of the richest treatments of this kind of analysis was in the *Glider* unit in "A World in Motion."

In contrast to engineering practice, the curricula provide few opportunities for analysis of the economic feasibility of a given design or of the relative feasibility of competing designs. However, economic factors that can influence design are addressed in "Building Math," "Design and Discovery," and "Engineering the Future." For example, in "Building Math," middle school students perform a variety of mathematical computations to design optimal interventions to contain the spread of a virus in a village in the Amazon rain forest on a budget of $10,000. In the "Design and Discovery" curriculum, students compare the costs and trade-offs associated with using different materials for beverage containers (e.g., aluminum, glass, plastic). In an exercise in "Engineering the Future" students perform simple calculations to estimate the cost of materials and production, project a retail price, and estimate the competitiveness of a product in the marketplace.

Many curricular materials encourage students to evaluate alternative design options. These analyses typically involve unstructured discussion among students working in a group about the perceived merits of each option to arrive at a consensus about which option should be further developed. For example, in "Building Math," middle school students design an insulated container of medicine that will maintain a temperature of 59°F to 86°F for a minimum of two hours. After gathering data about the insulating properties of various materials, each member of the design team sketches an idea for a container, describes it to the other members of his or her team, and then, "as a group," they "decide on one 'best' solution." None of the curricula include procedures or expectations for conducting a formal analysis of alternative solutions, such as a trade-off matrix for making quantitative comparisons of the strengths and weaknesses of competing designs (Garmire, 2002).

Investigating failure as a specific line of analysis appears in only a few curriculum projects. A good example, from the *Packaging and Other Structures* unit in the "City Technology" curriculum, requires elementary students to fill paper and plastic bags with containers of water until they fail. The

broken bags are then studied in detail to determine the nature and location of the failures, and the results of the analyses are used to develop proposals for improving the performance of the bags.

Constraints

We defined "constraints" as the physical, economical, legal, political, social, ethical, aesthetic, and time limitations inherent to or imposed upon the design of a solution to a technical problem. Our analysis suggests that constraints are a frayed fragment of thread running through some of the beads. The frayed nature of the thread indicates the ambiguities of the concept of constraints and the many ways it is interpreted.

In engineering practice, constraints frame the problem to be addressed by defining the salient conditions under which it must be solved. These conditions can include budget limitations, government regulations, patent laws, and project deadlines, among others. In the curricular initiatives that address this concept at all, constraints were presented as "things"—usually time, money, and materials—that limit the design process. However, "City Technology" includes rules and regulations among constraints on the design process. *Gateway to Technology* includes aesthetic considerations and the limits of human capabilities in its definition. A module on *Reverse Engineering* in the "Designing for Tomorrow" curriculum introduces the idea of constraints as limitations in materials properties and manufacturing processes.

Other factors in addition to constraints that can help define a problem include design specifications (i.e., features of the final solution, without which the design will not solve the problem) and design criteria (i.e., the parameters that must be tested to evaluate the suitability of final product). In the curricula, the terms constraints, specifications, and criteria are usually used interchangeably.

The confusion is most apparent in the learning activities. For example, in a design unit, *Power and Energy: The Whispers of the Willing Wind* from the "Invention, Innovation, and Inquiry" curriculum, constraints for the design and construction of a working model of a windmill are outlined. The "constraints" stipulate that the tower must be no more than 12 inches high, that the side of the base must not exceed 6 inches, and that the turbine must be less than 5 inches in diameter. The reasons for these specifications are not disclosed, but they do not appear to have a relationship to the problem being addressed or to reflect engineering design practices. Their purpose seems to

be to direct student behavior to ensure success, limit the amount of resources for the project, and make the teacher's management of the activity easier. This treatment of "constraints" is typical of many curricula we reviewed.

Modeling

We defined "modeling" as any graphical, physical, or mathematical representation of the essential features of a system or process that facilitates engineering design. Our analysis suggests that modeling is represented by a thin, varicolored thread running through most of the beads. The colors represent the different uses of modeling in engineering activities and in the teaching and learning process.

Engineers use models to help visualize potential solutions to design problems and/or as an interim step in the development of working prototypes. In many of the curricula, modeling is defined the same way. For example, in one unit in the "Engineering is Elementary" curriculum, a model is defined as "a small representation, usually built to scale, that serves as a plan." In the "Design and Discovery" materials, a model is defined as a "visual representation of a total design (or some aspect of the design) that is nonfunctional." In those same materials, a prototype is defined as a "working model used to demonstrate and test some aspect of the design or the design as a whole." In the *Gateway to Technology* unit of the "Project Lead the Way" curriculum, modeling is defined as "the process of creating three-dimensional representations of design solutions." Computer modeling is defined as "the use of computer software applications that allows the user to visualize an idea in a three-dimensional format."

As these characterizations suggest, most of the curricula engage students in making things, usually from everyday materials, to help them visualize their designs and present them to others. For example, in *Building Structures with Young Children*, students construct towers and enclosures using building blocks. In "Children Designing and Engineering," elementary students construct models of lighthouses and habitats for koalas. "Engineering is Elementary" projects engage students building models of windmills, water filters, paper bridges, alarm systems, and other objects. In "A World in Motion" projects, students construct and test toy vehicles (e.g., motorized cars, gliders). *Gateway to Technology* involves modeling cranes, magnetic-levitation trains, automated devices, airfoils, and rockets. "Material World Modules" involve the construction and testing of models of concrete roofing tiles, composite fishing poles, and humidity sensors. In "The Infinity Project"

activities, students use simulation software to model sound-effect generators, video systems, and computer networks.

In engineering practice, physical and mathematical models are also used to obtain data as a basis for making informed decisions during the design process. An example of this can be found in *Challenge Number 3*, a unit of "A World in Motion," in which eighth graders collect and graph data relating the center of gravity of a model glider to where the wing is placed and to the amount of weight in the nose of the glider. Based on the graphs, students predict optimal flight performance by determining the nose weight that locates the center of gravity closest to the centerline of the wing. Thus this curriculum has students use a physical model, the toy glider, to generate data for a simple mathematical model that represents the relationship between key variables that affect flight. The model is then used to adjust the design of the glider to achieve desired flight behavior. In a "Gateway to Technology" project, students use simulations posted on the Internet to model the effects of changing variables on the performance of rockets. Although the students interact with a mathematical model through the graphical model, the instructional materials do not call attention to the mathematical modeling.

For the most part, models are not used to represent key variables in the early stages of the design process but are presented as steps in the later stage of the design process for refining a relatively mature design solution to a problem. Thus models are used to visualize a design, take it to a higher level of refinement, and communicate its features to others. In many ways, this use of modeling is representative of industrial design rather than engineering design. Industrial design is the professional service of creating and developing concepts and specifications that optimize the function, value, and appearance of products and systems for the mutual benefit of both user and manufacturer (IDSA, 2008).

However, the reader should keep in mind that the pedagogical role of modeling is independent of its role in engineering design. Strategies to engage students in cooperative learning, such as Socratic dialogue, inquiry and design, and reflection and debriefing, typically involve making, testing, and presenting models. Modeling requires that students generate ideas, translate them into concrete form, and assess their validity. In the process, they must re-examine their assumptions, identify misconceptions and failures, refine their thinking, and develop and implement new ideas. Ultimately, models are embodiments of thought processes, insights, and discoveries in a form that communicates them to others.

Optimization

We defined "optimization" as the pursuit of the best possible solution to a technical problem in which trade-offs are necessary to balance competing or conflicting constraints. Our analysis suggests that optimization is a thin, translucent thread that is often obscured by other threads.

Most of the curricula do not explicitly address the concept of optimization. More often than not, optimization is embedded in lessons rather than called out as a key concept in objectives, laboratory activities, or assessment instruments. Optimization is most often embedded in the concepts of iteration (i.e., making incremental refinements during the development of a design) and redesign (i.e., analyzing an existing design to identify deficiencies or opportunities for improvement). In both cases, the goal is to improve a design. However, improving a design is not always synonymous with making trade-offs.

In most of the curricular materials, optimization is equated with "think harder" and "make it even better" as part of iteration and redesign. Improvements are often based on brainstorming rather than analysis, and little, if any, attention is paid to trade-offs. None of the curricula address the potential of using mathematics, especially for optimizing designs that are subject to economic constraints.

Trade-Offs

We defined "trade-offs" as decisions made to relinquish or reduce one attribute of a design in order to maximize another attribute. Our analysis suggests trade-offs are, like optimization, a thin, translucent thread.

The *Skimmer Design Challenge*, a unit in "A World in Motion," challenges students to make informed decisions about the size, shape, and position of a sail on a paper sled that skims across a tabletop pushed by a fan. In this exercise, students must make trade-offs among the size of the sail and the speed, distance, and stability of the sled. They must also determine the proper relationship between the weight of the sled and speed, distance, and stability. Finally, they must determine the orientation of the sail on the mast and the location of the mast on the hull.

In the *JetToy Design Challenge* in the same curriculum, students must determine the optimal relationship between inflation of a balloon, the diameter of the nozzle, and the duration and amount of propulsive force. They must also find the optimal weight of the vehicle in relation to its speed and the distance it can travel. This "tuning process" is informed by data

describing how each variable (nozzle size, balloon inflation, vehicle weight, and friction) affects vehicle performance (speed and distance).

Another example of trade-offs is embedded in the *Models and Designs* unit in the "Full Option Science System" curriculum. In the course of making and modifying a rubber-band-powered cart, the students are likely to engage in optimization because each challenge inevitably introduces unanticipated cause-and-effect relationships. For example, the size of the wheels affects how far the go-cart travels. If the wheels are bigger, the amount of force required to propel the go-cart may have to be increased. If more tension is applied to the rubber bands to propel the cart a greater distance, traction is likely to become an issue. The increase in tension is also likely to exacerbate the problem of friction. Each of these adjustments introduces the need for trade-offs. However, neither the concept of trade-offs nor the concept of making trade-offs in the interest of optimization is addressed directly in the curricular materials.

The unit on *Inquiry: The Ultimate School Bag* in the "Invention, Innovation, and Inquiry" curriculum includes the redesign and improvement of a backpack for carrying schoolbooks and personal items. Redesign intrinsically involves optimization, although the concept is not addressed directly here, either.

Some references are made to the concept of trade-offs in the *Building Structure with Young Children* unit in the "Young Scientist Series." Teachers are encouraged to prepare and ask questions about the advantages and disadvantages of different design options. For example, in the context of building a model house, teachers are encouraged to entertain ideas such as making the roof out of a lightweight material that requires less support but is not likely to be strong. If children chose to make a strong roof, they might also have to build in more support.

In the "Gateway to Technology" curriculum, trade-off is defined as "an exchange of one thing in return for another, especially relinquishment of one benefit or advantage for another regarded as more desirable." Although several assignments involve identifying the positive and negative impacts of various technologies, students do not directly address the balance between competing factors. For example, from a student's point of view, the main goal of an activity involving the building a compressed-air dragster is to design the fastest vehicle possible. In this exercise, speed is a function of the vehicle's mass, assuming that the propulsive force remains constant. Even though mass also affects the stability of the vehicle, the instructional materials do not require that students directly confront the trade-offs between mass, stability, and speed.

Systems

We defined a "system" as any organized collection of discrete elements (e.g., parts, processes, people) designed to work together in interdependent ways to fulfill one or more functions. Our analysis suggests that systems and systems thinking are fragments of thread interwoven with other, more continuous threads. By this, we meant that systems and systems thinking do not permeate any single curriculum. Both concepts are used selectively, often to help students analyze or explain how a technology works.

The committee's definition of systems is consistent with the definitions in the curricular materials that addressed systems in some manner. For example, "City Technology" explained systems as "a collection of interconnected parts functioning together in a way that make the whole greater than the sum of its parts." In "Engineering is Elementary," a system is defined as "a group of parts that interact to create a product"; in one unit it is defined as "a group of steps that interact to create a process." In the *Models and Designs* unit of the "Full Option Science Systems" curriculum, system is defined as "two or more objects that work together in a meaningful way."

The concept of systems is treated most directly in curriculum initiatives focused on domain knowledge. In these cases, systems thinking is often an undercurrent in the storyline of how a specific technology works. The same is true in "The Infinity Project for Middle School," which stresses that most technological systems follow a pattern of inputs, processes, and outputs. The materials provide illustrations of sophisticated systems in the form of simple flow charts that accompany explanations in the text of how the systems work; the illustrations are also organizers for laboratory activities related to such things as digital music, digital images, and data encryption.

The "Engineering is Elementary" and "Design and Discovery" curricula introduce the idea that systems can be divided into subsystems and that subsystems can be further divided into components. In the "Design and Discovery" curriculum, a laboratory activity is focused on analyzing bicycles in terms of systems, subsystems, components, and parts.

Several curricula featured units or lessons in which reverse engineering is used to engage students in studying simple devices from a systems perspective. These activities involve identifying parts, determining their function, uncovering relationships, discovering how they work together as a system, and identifying ways to improve their performance. This kind of systems thinking was the part of lessons in the "City Technology," "Design and Discovery," and "Designing for Tomorrow" curricula that ultimately engaged students in exploring opportunities for redesigning products.

In rare cases, systems and systems thinking are used to analyze the reasons a technology fails. One example is a module on *Reverse Engineering* in "Designing for Tomorrow." This module begins with a case study of failures associated with the space shuttle *Challenger* disaster. Through a simplified form of reverse engineering, the students, in theory, discover that the accident was caused by systems breakdowns in the NASA organization, as well as a failure in the space shuttle technology.

Reasons for Teaching Engineering

We were not surprised that the reasons for including engineering content in these curricula are as diverse as the materials themselves. It is surprising, however, that teaching engineering is not always a first-order objective. In most cases, the primary reason for including engineering is to enhance the study of science, mathematics, or both subjects. For example, the "Building Math" program uses examples from engineering to demonstrate "how math is used as a discipline of study and a career path." The materials in "A World in Motion" facilitate an "exploration of physical science while addressing essential mathematic and scientific concepts and skills." The "Insights (Structures Unit)" provides "students with exciting science experiences that extend their natural fascination with the world and help them learn the science skills and concepts they will need in later schooling and in life." Engineering materials in "The Infinity Project" provide "an innovative approach to applying fundamental science and mathematics concepts to solving contemporary engineering problems."

The materials designed to intensify learning in math and science and other core-curriculum subjects capitalize on the hands-on, interdisciplinary nature of engineering. For example, the goal of "Children Designing and Engineering" is to "develop innovative and unique contextual learning units that challenge students to think, act and share." Similarly, "Designing for Tomorrow" provides high school students with "high-quality interdisciplinary learning experiences that challenge them academically and develop their problem-solving, critical-thinking, and communication skills."

Sometimes the goal of enhancing the study of science and mathematics is more explicit. For example, *Building Structures with Young Children* makes "science the work and play of exploring materials and phenomena, while providing opportunities for children to learn from that experience." The "Building Math" program uses the study of engineering to demonstrate "how math is used as a discipline of study and a career path . . . [through]

. . . standards-based activities that integrate algebra and engineering using a hands-on, problem-solving, and cooperative-learning approach." The materials in "A World in Motion" are designed to facilitate an "exploration of physical science while addressing essential mathematic and scientific concepts and skills." The "Insights," "Material World Modules," and "The Infinity Project are all designed to improve science education and show how fundamental science and mathematics concepts can be applied to solve engineering problems.

Other curricula include engineering content to address the technological literacy needs of students. In the "City Technology" curriculum, the central purpose is to "engage elementary children with the core ideas and processes of technology (or engineering, if you prefer)." The goal of the "Engineering is Elementary" curriculum is "to harness children's natural curiosity to promote [the] learning of engineering and technology concepts." Similarly, the primary objective of the "Exploring Design and Engineering" initiative is to "help youngsters discover the 'human-made world,' its design and development." The "Invention, Innovation, and Inquiry" curriculum was created to "provide professional support for teachers interested in technological literacy in education."

Another more general goal of engineering curricula is to improve students' critical thinking. For instance, the goal of one "Gateway to Technology" unit is "to show . . . students how technology is used in engineering to solve everyday problems." "Engineering is Elementary" develops "interesting problems and contexts and then invite[s] children to have fun as they use their knowledge of science and engineering to design, create, and improve solutions." "Design and Discovery" "engages students in hands-on engineering and design activities intended to foster knowledge, skill development, and problem solving in the areas of science and engineering."

Only a few curricula define their objective as teaching engineering concepts and skills to prepare young people for further education and, ultimately, engineering careers. The Ford Partnership for Advanced Studies curriculum, "Designing for Tomorrow," encourages and prepares students "for success in college and professional careers in fields such as business, engineering, and technology." One of the central goals of "The Infinity Project" is to "help close the gap between the number of engineering graduates we currently produce in the United States, and the large need for high-quality engineering graduates in the near future." And PLTW materials "provide students with the rigorous, relevant, reality-based knowledge necessary to pursue engineering or engineering technology programs in college."

In interviews, many curriculum developers stated that teaching engineering knowledge and skills was not their primary objective. Their reasons for including engineering content included reversing poor test scores in mathematics and science, engaging students in more scientific inquiry, and showing students that mathematics has practical applications.

Several developers deliberately passed up opportunities to address engineering concepts and skills to focus on other problems or opportunities. Some explained that their projects were required to include enough science content to be considered part of science education, and that too much emphasis on engineering design, constraints, modeling, optimization, and technological systems could tip the scale toward engineering. They had to maintain a delicate balance, they said, with a modest bias toward science, to improve the chances that their materials would be accepted and implemented. Other developers said their materials were required to have enough mathematics content to be approved for elective credit in mathematics. Finally, some noted that in the current No Child Left Behind climate of accountability for student achievement in core subjects, there isn't much room for engineering content in the school curriculum.

Another factor that had to be taken into consideration was the comfort level (sometimes the discomfort level) of elementary, science, and mathematics teachers. Elementary teachers, for example, must have a deep understanding of child development coupled with skills in teaching reading, writing, and mathematics, but teaching about engineering is largely uncharted territory. Consequently, in several curricula, materials were configured to capitalize on teachers' strengths and teaching responsibilities by introducing engineering in conjunction with language arts, social science, and natural science instruction.

At the secondary level, many teachers are specialists with teaching assignments based on their training in a given discipline. Because engineering is often outside their areas of expertise, teaching engineering concepts and skills would require learning new content to implement new lessons, learning activities, and assessment methods.

Diffusion of Materials

The curriculum materials reviewed for this study range in maturity from more than 20 years old to just off the press, and they range in sophistication from units of instruction that can be downloaded from the Internet at no cost to programs featuring courses of study that span multiple grade levels

and involve formal commitments, professional development, and investments of large amounts of time, resources, and human capital. Much of the data on diffusion of these materials is limited to reports from curriculum pilot- and field-test sites, records of sales or dissemination of materials, and the number of teachers participating in professional development activities. However, none of these is a valid indicator of how widely a curriculum is used or whether it has been adopted by schools or school districts. Several developers of curriculum initiatives have entered into formal partnerships with participating schools and thus have mechanisms for structuring, supporting, monitoring, and assessing implementation. Table 4-2 summarizes what we have learned about the dissemination of these curricula.

Implementation and Costs

The costs for curricular materials range from $1,100 for a series of eight three-ring binders to no charge at all for a half-dozen large boxes of curricular and laboratory materials. The contents range from major curricular initiatives with no single objective to modest projects with more than 60. Some curricula can be implemented with everyday items at very little cost; others require large capital investments for specific, elaborate pieces of laboratory equipment.

Project Lead the Way (PLTW) has the most formal and systematic implementation process. For a school district to obtain and implement the curriculum, it must make a significant commitment to the program. This involves first submitting an application to become a PLTW site, then signing an agreement or memorandum of understanding that outlines the terms for participating in the program. The school district agrees to initiate a minimum of four courses within four years at the high school level, purchase required software through PLTW Inc., serve as a model program for other school districts, adhere to PLTW's implementation guidelines, ensure that teachers and guidance counselors complete PLTW's three-phase training program, establish an advisory committee or "Partnership Team," purchase equipment and supplies approved by PLTW, and participate in PLTW's systematic evaluation process.

Under this agreement, participating high schools must be certified by their second year in the program and recertified every five years thereafter. Certification, which is a requirement for participating in the PLTW testing process for earning college credit, includes a self-assessment, a site visit, and a classroom and portfolio review. Schools must demonstrate that they meet PLTW's quality standards for the professional development of teachers and

TABLE 4-2 Diffusion of Curriculum Materials (for selected programs)[a]

Curriculum	**Diffusion**	**Comments**
Project Lead the Way	The PLTW curriculum is used in all 50 states and the District of Columbia in 2,700 schools (2,000 high schools and 700 middle schools). About 600 high schools have completed PLTW's program certification process, and 34 middle schools have been recognized by PLTW's "School of Excellence Recognition Program." PLTW estimates that 225,000 students are currently enrolled in PLTW classes and that more than half a million students have taken at least one PLTW course.	
Materials World Modules	This curriculum has been used in about 500 schools in 48 states by some 35,000 middle shool and high school students. The U.S. Department of Defense uses MWM modules in 13 schools associated with military bases overseas. MWM materials are also used in 35 schools by 120 teachers and 1,200 students in seven cities and towns in Chihuahua, Mexico.	
Infinity Project	The high school course has been used in 350 schools in 37 states and some schools in several other countries. The materials are being used as an introductory engineering course at Southern Methodist University and DeVry University. A new set of middle school modules is being used in 20 schools in Texas.	The modules on robotics, sound engineering, rocketry, the engineering design process, and environmental engineering have been incorporated into mathematics, science, and technology classes.

Designing for Tomorrow	This curriculum, developed by Ford Partnership for Advanced Studies, is used in more than 300 schools in 26 states.	This program has been implemented in comprehensive high schools in urban and suburban settings, career and technical-education programs, freshman engineering courses at the college level, and historically black colleges and universities.
A World in Motion	This curriculum is used in all 50 states and in 10 Canadian provinces/territories. More than 65,000 AWIM kits have been shipped to more than 16,000 schools since 1990. The developer (Society of Automotive Engineers) estimates that more than 4 million students in North America have participated in AWIM activities (based on the assumption that the curriculum kits are reused an average of 2.6 times in classes averaging 24 students).	More than 17,000 engineers have volunteered in AWIM programs.
Engineering is Elementary	This curriculum is used in about 850 schools in 46 states and the District of Columbia. Based on sales figures and teacher participation in professional development workshops, the developer (Boston Museum of Sciences) estimates that about 15,000 elementary school teachers are using their materials. Approximately 1 million students have been exposed to the EiE curriculum since its inception.	Many fewer than 15,000 teachers—about 5,500—have received formal professional development to teach the EiE curriculum. The difference reflects estimates of teachers using the curriculum without having participated in an EiE PD program.

[a]These data are presented as reported by the curriculum developers.

counselors; the implementation of curriculum using required equipment and software; the formation and use of a Partnership Team, and more. The financial demands associated with implementing the program add up to tens of thousands of dollars over the course of several years, depending on course selection and existing laboratory resources. ("The Infinity Project" and "Designing for Tomorrow" have similar, but less formal requirements on a smaller scale.)

Several curriculum projects at the elementary and middle school levels offer resources to support implementation. The most comprehensive support is provided by "A World in Motion," "Children Designing and Engineering," "Engineering is Elementary," "Full Option Science System," and "Material World Modules." Implementation for these programs begins with the purchase of the instructional materials for the units of interest. These materials typically include teacher guides and, sometimes, videos or DVDs to support implementation. Student materials are presented as separate publications or reproducible master copies embedded in the teacher materials. "A World in Motion" requires participating teachers to involve a practicing engineer (a volunteer) in the delivery of the curriculum. The Society of Automotive Engineers (2009), which developed the curriculum, estimates that 17,000 engineer volunteers have participated since the program's inception.

Teacher materials typically cost $40 to $130, and classroom sets of student materials cost approximately $200. In addition, these programs offer kits of tools, supplies, and materials to facilitate the learning activities. The kits, which usually come in 4- or 5-cubic-foot containers that fit on a shelf or in a storage cabinet, cost $200 to $750, depending on the topic. "A World in Motion" provides the curriculum materials and kits free upon request, after a simple partnership agreement has been signed. Several projects also offer "refill packs" to replenish the consumables in the kits; these cost $20 to $250, depending on the nature of the materials.

Most of these curriculum projects maintain websites that can be used to purchase materials and kits, exchange ideas with other teachers, and tap into additional resources, such as lesson plans, links to relevant websites, a list of books and references, duplicate master copies, curriculum updates, safety data sheets, preparatory videos, discussion boards, additional learning activities, and professional develop materials.

Implementation of "City Technology," "Designing for Tomorrow," and "Invention, Innovation, and Inquiry" programs require purchasing one or more books and obtaining project-related tools and materials, which are available from popular suppliers, such as home stores, office supply stores,

discount stores, and vendors for science and technology education. Several recommend that tools and simple mechanical devices for analysis activities be obtained from garage sales or flea markets. Although these programs do not require large capital investments, they do require significant amounts of a teacher's time and energy. The tools, materials, and supplies necessary to implement these curricula must be located, purchased, counted, labeled, organized, and stored. Despite their low cost and simplicity, assembling these materials for laboratory activities is a time-consuming process that requires thoughtful preparation to minimize problems during instruction.

Pedagogy

To get some sense of how the curricula envision the teaching of K–12 engineering, our analysis included an effort to tease out the materials' pedagogical approaches. Of course, neither we nor our consultant, Prof. Welty, was able to spend time observing teachers teach or attending teacher professional development sessions. Thus what we present below reflects pedagogy inferred from the written materials rather than a firsthand account of what actually is occurring in classrooms.

Most of the curricular materials the committee reviewed rely on time-honored teaching strategies for facilitating learning. These strategies include beginning lessons with an anticipator set, activating prior knowledge, presenting new concepts, using questions to promote thinking, providing first-hand experiences, posing authentic problems for students to solve, debriefing students about their experiences, and engaging students in reflection.

All of the curricula emphasize hands-on learning activities that involve the application of concepts and skills being investigated. Most learning activities also focus on solving real-world problems (i.e., problems in contexts beyond the school walls). For example, the "Young Scientist Series" includes a unit titled *Building Structures with Young Children,* in which students use building blocks to erect enclosures to provide shelter for a toy animal. In the "Engineering is Elementary" curriculum, students build and test models that address problems related to harnessing wind power, filtering water, moving materials in a factory, building a footbridge that spans a stream, and more. In the "Building Math" curriculum, middle school students address problems related to keeping medicine cool in a tropical environment, collecting rainwater in the absence of fresh water, and designing insulated clothing that allows for easy movement. In "The Infinity Project," high school students use simulation software to develop and test a system that counts the animals

entering and leaving a given area in a refuge. Some curricula, however, do focus on problems that arise in schools. For example, the "City Technology" curriculum engages students in studying and addressing problems related to classroom interruptions, procedures, and layout.

In most of the curricula, teachers use a Socratic approach in conjunction with hands-on learning to actively engage students in learning. Questions are often used to reintroduce prior knowledge and experiences, solicit preconceptions that can be reassessed, launch and guide investigations, build and check for understanding, debrief students about their experiences, and facilitate reflection.

Some of the instructional materials are designed to follow a specific instructional model. For example, all of the units in "Engineering is Elementary" follow a sequence of lessons built on one another. The first lesson provides introductory activities that prepare students for the unit. The second lesson uses a fictional engineering story as an advanced organizer for the rest of the unit. The lesson that follows the reading is designed to orient students to a specific field of engineering (e.g., mechanical engineering, civil engineering, and agricultural engineering). The fourth lesson engages students in hands-on activities that address relationships between science, math, and engineering. All of the units end with engineering design problems consistent with the ones presented in the fictional account.

"Material World Modules" at the middle school and high school levels follow a similar pattern. Each module has three basic elements. Instruction begins with an introductory activity designed to stimulate interest in the topic at hand; this activity requires that students formulate a hypothesis about a cause-and-effect relationship. Second, students engage in four or five hands-on learning activities that introduce key principles, ideas, and methods related to the topic; these activities are framed in the context of one or more design problems. Third, students participate in a design project to develop a prototype product, applying the previously introduced science concepts and skills.

A prominent feature in several curricula is an emphasis on people and storytelling. For example, the "Design and Discovery" curriculum features stories about the history of the paper clip, the development of Kevlar™ by Stephanie Kwolek, the design of a bicycle for women by Georgina Terry, and so on. The textbook for "Engineering the Future" reads like transcripts of talks by a series of guest speakers who tell personal stories about their interest in engineering and their work. "Designing for Tomorrow," includes case studies of the development of the S.C. Johnson Administration Build designed by Frank Lloyd Wright, the space shuttle *Challenger* disaster, and so

on. "Models and Design" includes stories about Henry Ford's Model T, the cartoonist Rube Goldberg, and NASA's use of simulation technology.

Evidence of Diversity

Gender and ethnicity play an important role in the development of a person's self-efficacy, identity, approach to learning, and career aspirations (see, for example, Bandura et al., 1999; Maple and Stage, 1991). As noted in Chapter 2, engineers in the United States have historically been predominantly white males; and women, African Americans, and Hispanics are still significantly underrepresented in the profession. Exposing students to images of engineers who look like them and to engineering-related activities that resonate with their personal and cultural experiences may not only improve their understanding of engineering but may also make engineering more appealing as a possible career (EWEP, 2005; NAE, 2008).

Efforts have been made in several curricula to portray engineering as an interesting and accessible career for individuals from diverse backgrounds. For example, the textbook for "Engineering the Future" features 31 stories (or chapters) written by engineers, designers, architects, technologists, and technicians, almost half of them women and a third members of minority groups. Similarly, "Design and Discovery" includes vignettes that enable students to "meet engineers," half of whom are women. Every unit in the "Engineering is Elementary" curriculum features a story about a child who uses basic engineering principles to solve a problem. The main characters in four of the nine units are female, and all of the characters come from different ethnic backgrounds. In addition, several stories include adult females as mentors and advisors.

In contrast, stories in the "Models and Designs" unit of the Full Option Science System curriculum are dominated by male inventors, scientists, engineers, and industrialists (e.g., Stephen Hawkings, Dick Covey, Rube Goldberg, Henry Ford, Eli Whitney). In addition, almost all of the photographs of people engaged in scientific and engineering pursuits are male.

Several curricula focus on topics and projects that research suggests are more likely to appeal to boys than to girls.[4] For example, "A World in Motion," "Gateway to Technology," and "Models and Designs" include

[4]There is an extensive literature on gender preferences related to technology and engineering (e.g., Weber and Custer, 2005) that suggests, among other things, that girls are more interested in socially relevant technologies, while boys are more interested in how technologies work, and that girls prefer collaborative work, while boys are more motivated by competition.

major learning activities that involve designing, making, and testing model structures or vehicles (e.g., towers, bridges, cars, rockets, airplanes, boats). Other curricula feature lessons and learning activities that capitalize on the knowledge and experience of both male and female students. For instance, in the "Design and Discovery" curriculum, engineering concepts and skills are applied to designing paper clips, improving the caps on tubes of toothpaste, and analyzing bicycle systems. "City Technology" introduces engineering principles in conjunction with testing the design and strength of shopping bags, designing packages, making maps, establishing classroom procedures, analyzing pump dispensers, and building shelves. In the interest of inclusiveness, the "Infinity Project" deliberately focuses on technologies likely to be found in a high school student's backpack (e.g., digital music players, digital camera, cell phone, etc.). Activities in "Designing for Tomorrow" involve the reverse engineering of simple kitchen devices and training cups for small children.

We were interested not just in the implicit or explicit messages conveyed through these curricula, but also in the diversity, or lack of diversity, in the student populations that used these materials. The committee was particularly interested in how many girls and underrepresented minorities had an opportunity to participate. Unfortunately, only one of the curriculum projects we reviewed in depth collects demographic data on student participation.

A program evaluation of PLTW for the 2006–2007 school year showed that the number of African American and Hispanic students in schools that used this curriculum was proportional to the populations in the states in which the schools were located (Walcerz, 2007). However, African American students were slightly underrepresented in PLTW classrooms compared with their numbers in most PLTW schools. Girls were dramatically underrepresented throughout the program; they comprised just 17 percent of all PLTW students that school year.

The number for girls cited above is similar to the percentage of entry-level female college engineering students (NSF, 2005) but is well below the proportion of females in the overall U.S. population, which is slightly more than 50 percent (U.S. Census Bureau, 2005). PTLW is taking steps to increase the program's appeal to women and underrepresented minorities, such as participating in an NSF-funded Engineering Equity Extension Service project[5] and partnering with the National Action Council for Minorities in

[5]For information about the project, see *http://www.nae.edu/nae/caseecomnew.nsf/weblinks/NFOY-75WLB5?OpenDocument.*

Engineering to start 100 academies of engineering under the auspices of the National Academy Foundation.

PROFESSIONAL DEVELOPMENT

As yet, there is no clear description of the knowledge and skills needed to teach engineering to children. Nor do states license or certify teachers of engineering the way they do teachers of science, mathematics, technology, and other subjects. Most instructors who teach engineering in middle and high schools have a background in technology education;[6] a smaller number have backgrounds in science education; and an even smaller number have backgrounds in engineering. Because engineering is a developing area of content for K–12 schools, professional training for teachers in this field is still in its infancy.

Teacher "content knowledge" can be thought of as having three dimensions. First, teachers must know the subject they are teaching, in this case engineering, and its organizing principles. Second, they must have curricular knowledge, that is, an understanding of the materials and programs available to deliver the content. Third, they must have pedagogical content knowledge, which has been defined as "that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding" (Shulman, 1987).

Building on Shulman's work, Ball et al. (2008) have identified subcategories of subject-matter knowledge and pedagogical-content knowledge that reflect the specialized understanding unique to teaching. First, teachers must have "knowledge of content and students," which means they must be able to predict what students will find interesting, motivating, and difficult and to interpret students' incomplete thinking. Second, teachers need "knowledge of content and teaching," which implies they must be able to sequence particular content for instruction, for example, or evaluate the advantages and disadvantages of various representations of specific ideas.

To get a better understanding of how teachers acquire knowledge and skills to teach engineering to K–12 students, the committee looked into a number of programs that provide pre-service and in-service professional-development programs. Two committee workshops, in October 2007 and February 2008, were substantially devoted to this topic and are summarized in what follows.

[6]For example, 67 percent of teachers delivering the Project Lead the Way curriculum have a teaching certificate in technology education (R. Grimsely, PLTW, personal communication, June 16, 2009).

In-Service Programs

Most of the professional-development activities we identified are in-service rather than pre-service programs that provide supplemental education based on specific curricula for teachers already working in the classroom (Table 4-3). One advantage of well-designed, curriculum-focused professional development is that teachers come away with in-depth understanding of the purpose of the materials and first-hand experience with some of the difficulties and successes students might encounter. A disadvantage is that potentially useful and important content or pedagogical knowledge that is not included in the curriculum will be omitted.

Education researchers have identified common characteristics of effective in-service professional development programs for teachers. In a discussion of in-service programs for K–12 science educators, Mundry (2007) identified the following requirements:

- clear and challenging goals for student learning,
- adequate time, follow-up, and continuity,
- coherence with local policy, teachers' goals, and state standards,
- active, research-based learning,
- critical reflection on practice to support a collaborative professional culture, and
- evaluation of teacher and student gains resulting from the professional development.

Mundry notes that professional development sustained over time is more likely to be coherent, have a clear focus, and support active learning than "one-shot" workshops and other limited interventions. Opinions differ on the necessary number of hours, but most experts agree that single experiences are not likely to support teacher competence or confidence (e.g., NCES, 2001).

Research at the NSF-funded National Center for Engineering and Technology Education (NCETE) has focused on identifying the requirements for preparing technology educators to teach engineering. One small, qualitative study identified about a dozen interrelated factors that are important to preparing teachers to introduce engineering design concepts into the K–12 classroom (Asunda and Hill, 2007). A member of the NCETE leadership team told us that professional development planned jointly by engineering and technology education faculty resulted in better outcomes for teachers

than professional development planned by either one alone (Hailey et al., 2008).

NCETE also conducted an observational analysis of five professional-development programs, including three (Engineering the Future, Project Lead the Way, The Infinity Project) whose curricula we reviewed (Daugherty and Custer, unpublished). Among the study's findings were that (1) most of the programs were run by the curriculum developers, who rarely had a background in teacher professional development; (2) science, technology, and mathematics teachers have different professional development needs; and (3) hands-on activities were a very common element in the programs, but little instructional time was devoted to metacognitive reflection about either the teacher or student learning involved.

Although not all in-service programs for K–12 engineering teachers have all of the required features listed above, professional-development programs can have a dramatic impact on how widely the curriculum is used. A good example is "A World in Motion," developed by SAE International, which was launched in 1990; the first professional-development component was not added until 2005. Matthew M. Miller, manager of SAE's K–12 education programs, told us at the February 2008 workshop that the use of the curriculum doubled and the number of new classroom volunteers increased almost tenfold once the professional-development program was implemented.

Project Lead the Way (PLTW) has a very organized professional-development effort, which may, in part, explain its rapid growth. PTLW conducts two-week summer institutes, during which prospective PLTW teachers are immersed in the course they plan to teach, including completing all of the hands-on projects. PLTW has agreements with 36 universities to supply engineering faculty who team teach with PLTW master teachers to run the program. According to PLTW, about 7,200 teachers have taken part in the summer training sessions. Teachers who complete the course receive a certificate allowing them to teach the course. Ongoing assistance is available from PLTW through an online Virtual Academy (*www.pltw.org/moodle*).

Other in-service programs run the gamut from one-week summer institutes (e.g., "The Infinity Project") to self-paced coaching provided on a DVD included in the curricular materials for "Building Math"(Table 4-2).

Pre-Service Initiatives

Pre-service training of teachers has some distinct advantages over in-service training. The biggest difference is that teachers have longer exposure

TABLE 4-3 In-Service Professional Development Programs for Teachers of K–12 Engineering

Program/ Curriculum	Scope of Training	Target Audience	Training Force	Number of Teachers Reached	Notes
Project Lead the Way	All teachers are required to complete a two-week summer institute	Middle school and high school teachers, mostly technology educators	160 master teachers; 120 affiliate professors	7,200 teachers and 5,000 guidance counselors have been trained in all 50 states	Online Virtual Academy provides ongoing support
Engineering is Elementary	Optional training that varies from two-hour workshops to two-week sessions and semester-long programs	Elementary generalists	Professional development staff at the Boston Museum of Science	5,100 teachers in 28 states and the District of Columbia (as of June 2009)	A memorandum of understanding between the Boston Museum of Science and Valley City State University allows Engineering the Future to be used in VCSU online pre-service technology teacher education

City Technology	Optional training—a one-hour introductory workshop followed by 30-minute workshops on particular units	Elementary generalists, special education teachers, elementary science specialists, secondary math and science teachers, museum educators, after-school program staff, and parents	Authors of the curriculum (City College of New York)	Several thousand teachers and informal educators in about 20 states
Children Designing and Engineering	Required: 30-hour graduate course	Elementary teachers	In Virginia, the training is conducted through George Mason University	1,300 teachers since 1999 in six states, the bulk of whom (800) are participants in Virginia's Children Engineering Program

continued

TABLE 4-3 Continued

Program/ Curriculum	Scope of Training	Target Audience	Training Force	Number of Teachers Reached	Notes
Engineering Our Future New Jersey (based on the following curricula: Engineering is Elementary, World in Motion, Engineering the Future)	One- or two-day workshops	Elementary, middle, and high school teachers	Staff at the Stevens Institute of Technology	35 teachers in New Jersey	Planned expansion will reach 2,000 teachers
The Infinity Project	Required one-week summer institute	High school teachers		500 teachers in grades 9–12	Training includes an online discussion board for teachers
Material World Modules	Optional workshops that vary in length	High school teachers			
Engineers of the Future (training based on several different curricula)	Summer institute	High school and middle school technology educators, and elementary teachers		Nearly 700 trained, the majority using the Engineering is Elementary curriculum	Supported by $1.7 million grant from the New York State Education Department

Engineering the Future	Half-day, full-day, and multiple-day sessions in the Boston area and 20 to 40 hour moderated online professional development course	High school teachers			A memorandum of understanding between the Boston Museum of Science and Valley City State University allows Engineering the Future to be used in VCSU online pre-service technology teacher education
Building Math	Training DVD supplied with curriculum materials				
INSPIRES	Two-day workshops	Technology teachers in Maryland			
A World in Motion	One-day workshop	Elementary, middle, and high school teachers		65,000 kits shipped since 1990 (not clear how many teachers trained)	Teachers must agree to work with an engineer who volunteers in the classroom

times to concepts and skills, including math and science skills, necessary to teach engineering. The committee was able to identify just three programs that offer pre-service education to prepare individuals to teach engineering in K–12 classrooms.

Leveraging its model of in-service professional development, PLTW is working toward "infusing" its K–12 curriculum into teacher-preparation programs at nine university partners that already serve as sites for PLTW in-service summer institutes. The infusion of PLTW coursework into existing teacher-preparation curricula must be carefully planned to ensure that it aligns with state licensing requirements (Rogers, 2008). As of early 2009, fewer than 10 teachers had graduated from the new PLTW-infused programs (Richard Grimsley, Project Lead the Way, personal communication, January 5, 2009).

In contrast to PLTW's curriculum-focused approach, in 2002 the College of New Jersey (TCNJ) initiated the Math/Science/Technology (M/S/T) interdisciplinary degree program for aspiring elementary school teachers that requires coursework in all four STEM subjects. The program is a collaborative effort by the schools of engineering, education, and science administered by the Department of Technological Studies in the School of Engineering. The 32-credit program (Box 4-1) now has more than 150 graduates and current majors and is one of the fastest growing majors at TCNJ (Karsniz et al., 2007).

Students who matriculate from the M/S/T program appear to have an appropriate background for teaching engineering. Unfortunately, TCNJ does not track the employment histories of its M/S/T graduates who, according to school officials, are in great demand as science and math teachers (John Karsnitz, TCNJ, personal communication, September 20, 2007). So, at least for now, the TCNJ program does not appear to be contributing to the national supply of engineering teachers.

In 2006, Colorado State University in Fort Collins established a joint major in engineering and education. To the committee's knowledge, this is the only program of its kind in the United States. Students in the program must complete general-education requirements, core engineering requirements, engineering-school electives, and professional education requirements. In the first year, 11 students (70 percent of them female) were enrolled in the program. Graduates will receive an engineering degree and a teaching license (DeMiranda, 2008).

Other models of pre-service engineering education for teachers exist. For example, at Boise State University, students majoring in elementary

BOX 4-1
The M/S/T Major at TCNJ

The M/S/T program provides 10 units of "liberal learning" courses, such as creative design, calculus A, and a natural science. The 12-unit M/S/T academic major has an eight-unit core, which includes courses in multimedia design, structures and mechanics, two additional science courses, and one additional math course (either calculus B or engineering math). Areas of specialization must include four additional units in technology/pre-engineering, mathematics, biology, chemistry, or physics. Specialization is the equivalent of a minor in one of the disciplines and may require that specific courses be included in the core requirements. M/S/T students who major in education must also complete 10 units of professional education courses. Such students meet New Jersey's certification requirements for highly qualified teachers. In addition to primary K–5 certification, M/S/T majors can apply for an endorsement for teaching middle school mathematics or science, if they have completed 15 credits of coursework in the discipline and have passed the appropriate PRAXIS test. They may also receive technology-education certification, if they have completed at least 30 specified credits and passed the appropriate PRAXIS test.

SOURCE: Karsnitz, 2007.

education may enroll in an introductory engineering course offered by the College of Engineering. The course is supplemented by a seminar led by education faculty that considers how engineering projects can be used in the K–12 classroom to meet state teaching standards for math and science as well as reading, writing, and other non-technical subjects (Miller and Smith, 2006).

Through a collaboration with TERC (*www.terc.edu*), Lesley University and Walden University offer an online course, Engineering: From Science to Design, for education master's degree candidates. The course includes independent, hands-on work and group feedback and discussion in facilitated online forums (Sara Lacy, TERC, May 15, 2008).

At least two states have started programs to provide new K–12 teachers with STEM credentials. In California, the University of California, California State University, and state and industry leaders initiated Cal Teach (*http://*

calteach.berkeley.edu/), which recruits students majoring in math, science, and engineering to become K–12 teachers. The goal of Cal Teach is to have 1,000 teachers in place by 2010. A similar effort, UTeach (*http://uteach.utexas.edu/*), was launched in 1997 at the University of Texas at Austin. As of 2007, the program had graduated a total of 480 STEM students, 41 of whom had degrees in engineering in addition to teaching certificates (376 had degrees in the natural sciences) (University of Texas at Austin, 2007). Under the auspices of the National Math and Science Initiative, UTeach has been expanded to 13 additional colleges and universities across the United States.

OBSTACLES FACING PROFESSIONAL DEVELOPMENT PROGRAMS

Based on information provided during the two preliminary workshops and in the research literature, several barriers to professional development programs must be overcome in preparing educators to teach engineering in K–12 classrooms. For instance, teachers who are not familiar with engineering may feel anxious and apprehensive, which can inhibit the effectiveness of professional development programs. Christine Cunningham, the director of professional development for "Engineering is Elementary," described the problem (Cunningham, 2007):

> If most elementary teachers are afraid of teaching science, the notion of teaching engineering is often accompanied by terror. Much of the point of our professional development is to defuse their feelings of ineptitude through engagement.

Similarly, teachers who do not have adequate knowledge of science and, especially, mathematics sometimes have difficulty understanding the material. In addition, some have little, if any, desire to take part in training activities (Diefes-Dux and Duncan, 2007). Reportedly, some teachers also are uncomfortable with the open-endedness of engineering design. "A major challenge in PD for K–12 engineering is to undo the mindset that sees answers as right or wrong, and as complete or incomplete," note Benenson and Neujahr (2007). In a survey of 44 technology teacher-education programs, only 17 percent had completed the mathematics and science courses that would qualify them to teach PLTW courses (McAlister, 2005). McAlister also found that, when a group of 43 technology teachers was presented with two fairly simple problems involving structural load, half of them indicated that they would require additional training before they could teach those

problems to students. Only one was able to identify the correct formula for solving one of the problems.

INSPIRES (INcreasing Student Participation, Interest and Recruitment in Engineering & Science), a small-scale professional-development program at the University of Maryland, Baltimore County, relies on engineering faculty to lead some activities. The program leaders note, however, that large numbers of engineering faculty might not be able to participate in such ventures because of their workloads and because of typical university reward structures (Ross and Bayles, 2007). More systemic problems, such as a lack of understanding of program content and learning progressions, may also interfere with the effectiveness of professional-development programs for K–12 teachers of engineering (Hailey et al., 2008).

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Annex

PRE-UNIVERSITY ENGINEERING EDUCATION IN OTHER COUNTRIES[1]

Given the universality of science and technology, the committee felt it appropriate to look into how other nations encourage engineering thinking in pre-college students. However, because of budget and time constraints,

[1]This appendix is adapted from a paper written for the committee by Dr. Marc J. DeVries, Eindhoven University, The Netherlands, based on research conducted by Carolyn Williams, a 2007 Christine Mirzayan Science and Technology Policy Graduate Fellow at the National Academy of Engineering.

BOX 4A-1
Selected Countries with Pre-College Engineering Programs

England/Wales: General Certificate of Education, Engineering
Australia (New South Wales): Higher School Certificate in Engineering Studies
Israel: ORT Innovative Science Track in Engineering Sciences
Germany: Junior-Ingenieur-Akademie (Academy for Junior Engineers)
South Africa: Further Education and Training in Electrical Technology
France: Baccalauréat General, Série Scientifique Sciences de l'Ingénieur; Baccalauréat Technologique, Série Sciences et Technologies Industrielles
Netherlands: Technasium, Research and Design
Colombia: Pequeños Cientificos (Little Scientists)

the committee did not pursue this research and analysis with the same intensity as it had for U.S. efforts. In addition, because of differences in the organization and operation of educational systems in other countries, it was difficult to draw direct comparisons with the situation in the United States. Materials in languages other than English further complicated the analysis, and curricular documents were not always available. In many cases, the curriculum content had to be inferred from a review of sample assessment items. Despite these limitations, the committee was able to identify several important principles.

The committee used a variety of information-gathering techniques, including online searching; telephone interviews; and e-mail requests to professional, corporate, academic, government, and education groups and individuals. Eight programs or projects in eight countries were identified (Box 4A-1), all but one of which (Pequenos Cientificos) were for senior secondary-level students (i.e., grades 10–12). In all probability, these eight initiatives represent only a fraction of these kinds of activities around the world.

The Goals of Pre-College Engineering Education

Two primary purposes were identified for exposing pre-college students to the study of engineering—"mainline" goals (i.e., general education) and

"pipeline" goals (i.e., preparation for engineering careers). The majority of programs were in the "pipeline" category. In France, for example, preparation for the academic study of engineering is preceded by a competitive selection process at the pre-college level with the goal of identifying the very best students for continued engineering education. Based on sample exam questions for prospective engineers in Israel, the committee inferred that the emphasis of the ORT engineering sciences program is on preparing students for post-secondary engineering education, rather than on expanding their general education.

Programs in some countries seem to serve both purposes. For example, in England and Wales, the General Certificate of Education, Engineering, has some features in common with the U.K.'s Design and Technology Curriculum, which is designed primarily for general education purposes. At the same time, to receive a General Certificate, students must master a good deal of specific knowledge in engineering domains, thus preparing them for further engineering studies.

Treatment of Engineering Concepts and Domains

The focus on core engineering concepts in international programs varies greatly. The U.K. materials, for example, treat the concepts of systems and control in some detail, while other concepts, such as optimization, are largely absent. The design process is evident, consistent with the influence of the design and technology paradigm. In the Israeli programs, the curriculum and sample exam questions focus on the concept of systems; related ideas, such as control, feedback, and parameters, are also treated in some detail. By contrast, the South African assessment materials have few explicit references to general engineering concepts; instead, they focus on ideas specific to electrical engineering, most of which are scientific rather than engineering concepts (e.g., voltage, current). Exam questions in the French Série de Sciences de l'Ingénieur explicitly refer to engineering concepts, including system analysis, requirements, and optimization.

Overall, the international pre-college engineering programs include a wide range of engineering domains. The U.K. General Certificate of Education, Engineering, reflects the compulsory pre-college design and technology curriculum; thus it explores the traditional disciplines of electrical and mechanical engineering, as well as less traditional areas, such as food technology and biotechnology. The exam questions for Australia's Higher School Certificate in Engineering (HSCE) Studies address issues in telecom-

munications, transportation, civil engineering, aeronautics, and electronics; the exam also includes a biotechnology module.

In addition to two engineering sciences courses, students pursuing the Israeli ORT curriculum pick a specialization course from one of the following areas: motion systems, biomedical engineering, robotic systems, artificial intelligence, or aerospace engineering. The content of the sample exam for the ORT curriculum, however, appears to focus on computer programming. The French baccalauréat programs cover a variety of engineering domains spread over different 'séries' in the 'bac'. In the engineering series, the focus is on electrical engineering, mechanical engineering, and information science.

Treatment of Science, Technology, and Mathematics

International pre-college engineering initiatives appear to face same challenges as U.S. initiatives, such as teaching students to use math and science to solve or optimize authentic design challenges. In the French curriculum, math and science are integrated, but at a high level of difficulty. Exam questions for the 'Séries de Sciences de l'Ingénieur' describe a technical device that has to meet a given set of requirements, and students are asked to calculate certain variables based on their knowledge of science.

In most instances, however, math and science concepts are treated as separate from technological content. For example, sample assessment items for the Australian HSCE require the application of scientific knowledge and mathematical skills to problems specific to technical devices. Either the technical device is used as a context for asking a question that requires knowledge of science and/or math, or the question is about technology and does not require science or math.

The same separation was evident in exam questions and practical assessment tasks in the South African curriculum. The exam includes questions about abstract situations (e.g., diagrams representing electrical and logical circuits) in which students must make calculations and apply their knowledge of the laws of electricity. The practical assignments are design challenges, but they do not encourage the application of science or math to develop or optimize the design solution.